

Tuning the PXIE RFQ

PXIE RFQ Fabrication Readiness Review
LBNL - June 26, 2013

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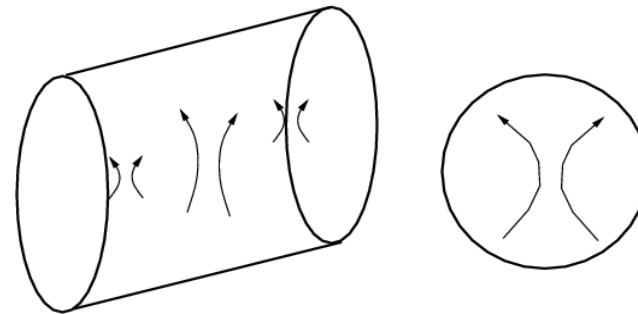
Field Configuration in the RFQ

The RFQ operates in the TE_{210} mode with modified boundary conditions at the end walls to provide a flat field distribution.

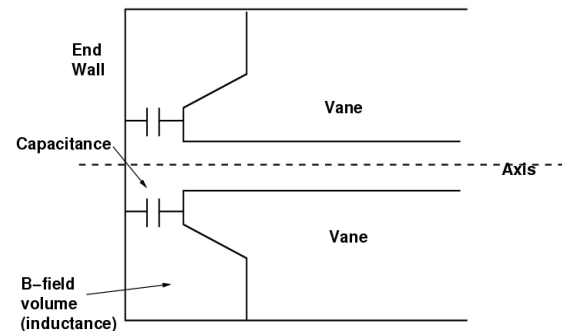
A pillbox cavity cavity has no transverse field at the ends.

The ends of the RFQ are modified to present a termination at the waveguide impedance that allows a constant field all the way to the end of the vane.

Example: TE_{110} in a pillbox:
no fields at ends



The ends of the vanes are resonated with cutbacks that allow a non-zero transverse field at the ends.



End Resonance vs. Body Resonance

The overall resonance is determined by the TE_{210} mode resonance of the RFQ body, along with the resonance of the end region.

If these individually differ, the field configuration along the vane will be perturbed.

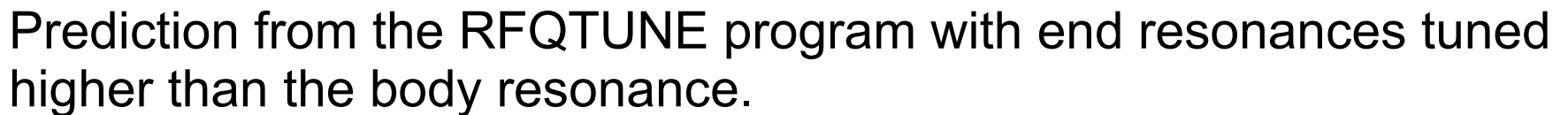
The RFQ is a standing wave cavity, and the field variation along the structure is determined by local frequency variations along the structure.

$$\frac{d^2}{dz^2} \left(\frac{\delta E_0}{E_0} \right) = \frac{8\pi^2}{\lambda^2} \frac{\delta f_0}{f_0}, \quad \int \frac{\delta f_0}{f_0} dz = 0$$

This is a second-order diff eq with two constants of integration: initial field, and initial field slope. However, zero integral of local frequency variation (second equation) reduces this to one constant.

Consequence: **local frequency error down causes a local field error up.**

What happens if the **ends** of the RFQ are not tuned to the **body** frequency?



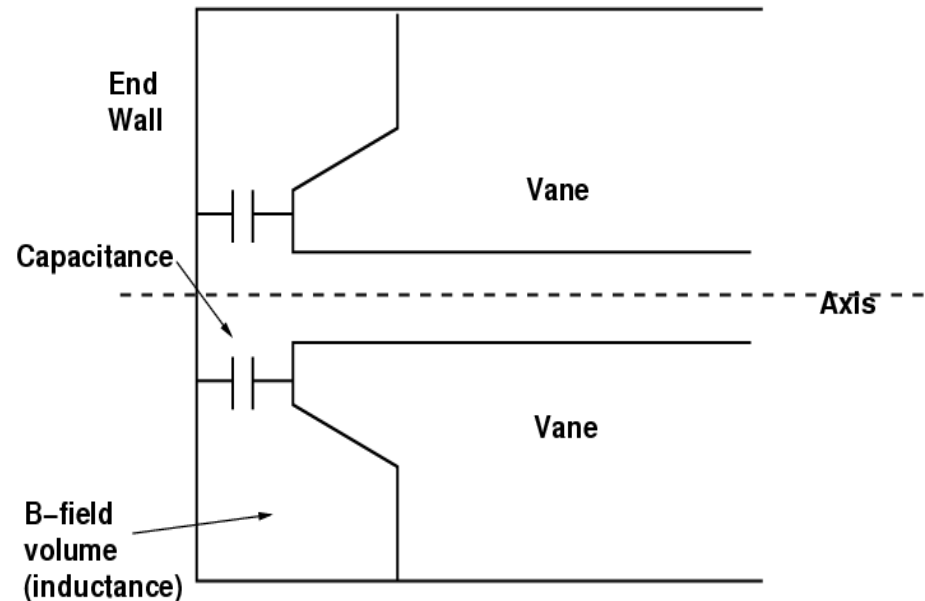
One end high, the other low gives an overall **tilt**.



End Terminations

The end of the RFQ vane is short of the end of the cavity.

The spacing from the end is a capacitance that resonates with the inductance in the volume of the cutback.



The dimensions of the cutback affect the end termination impedance at resonance. The cutback region is determined with 3-D electrodynamics simulations, and the capacitance due to the spacing from the end of the vane to the endwall is determined empirically.

Structure Stabilization

The RFQ is a standing-wave structure whose voltage flatness sensitivity to local frequency variation goes as the square of the cavity length.

In addition, the existence of the vanes loads the TE_{210} frequency down to very near the TE_{110} frequency.

The TE_{110} dipole mode steers the beam off axis and is excited by geometrical errors.

Increasing the mode separation reduces the machining and assembly tolerances.

Pi-mode stabilizers moves the TE_{210} frequency down, the TE_{110} frequency up, and has the effect of locking the field amplitude in all four quadrants together.

This significantly eases the process of tuning, as quadrupole symmetry is enforced. Tuners are set in groups of same longitudinal position, collapsing the the problem of 80 tuners down to 20 tuners.

Tuning Individual Modules

The RFQ comprises 4 modules, each about a meter long.

The first and last module have vane cutbacks, not identical to each other, and the central modules have no cutbacks at all.

If the frequency of a single module is to be determined before brazing, a cold assembly is performed. If a central module is dry-tested, it will require a temporary cutback at each end.

Tuning of individual modules is not likely to predict the field flatness of the entire RFQ of 4 modules, as local errors have $4^2 = 16$ times the effect on the field distribution than they do for an individual module.

However, a dry test of a single module is of use to determine whether the module is on frequency. But the measured frequency of an individual module is highly dependent on the frequency of the ends.

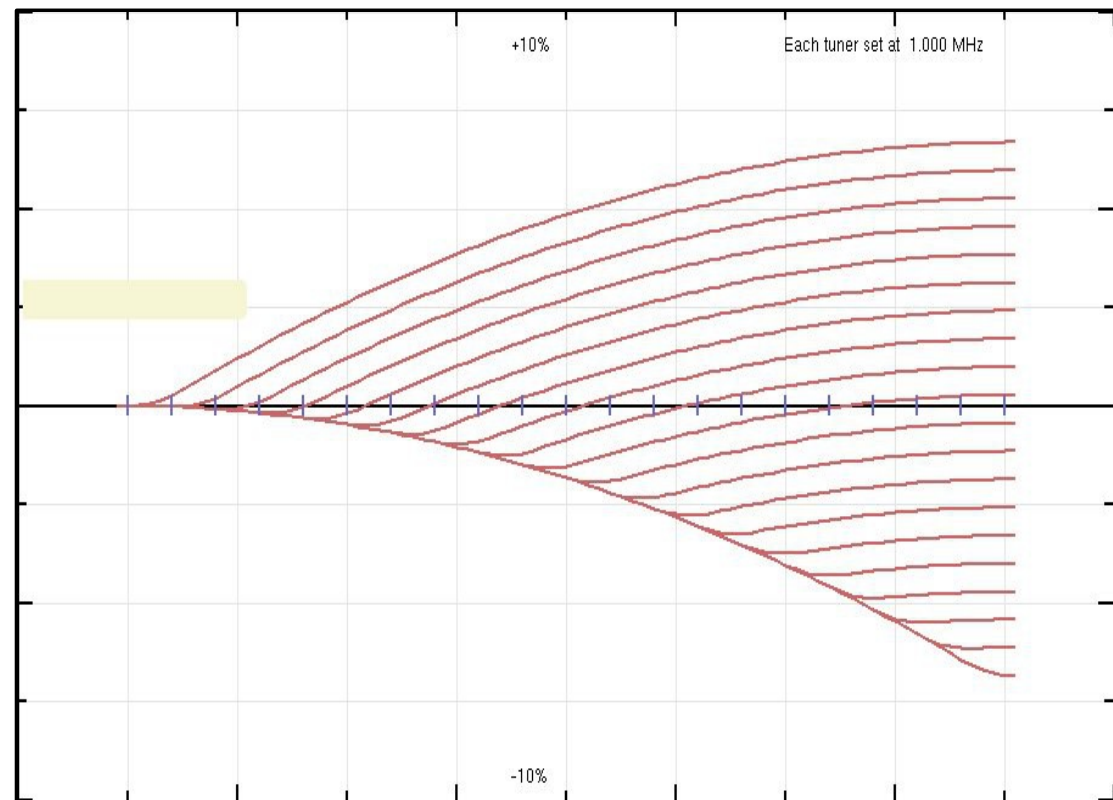
Basis Vector Set with 20 Tuners

20 tuners (in each quadrant, 80 altogether) to adjust $E(z)$

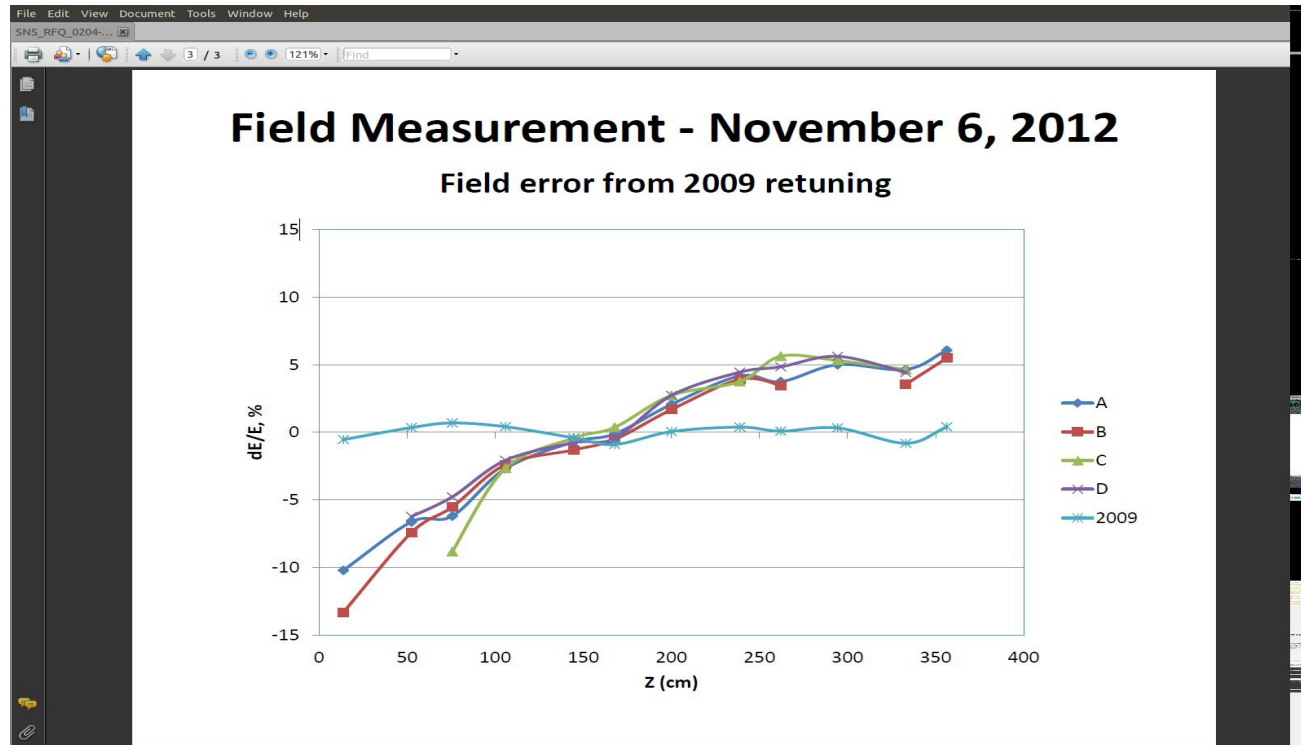
Definitely not an orthogonal set of vectors.

Field variation produced by each tuner, one at a time, with the same boundary conditions at the left.

All corrections will be a linear sum of each of these basis vectors.



Example, SNS RFQ Field Adjustment

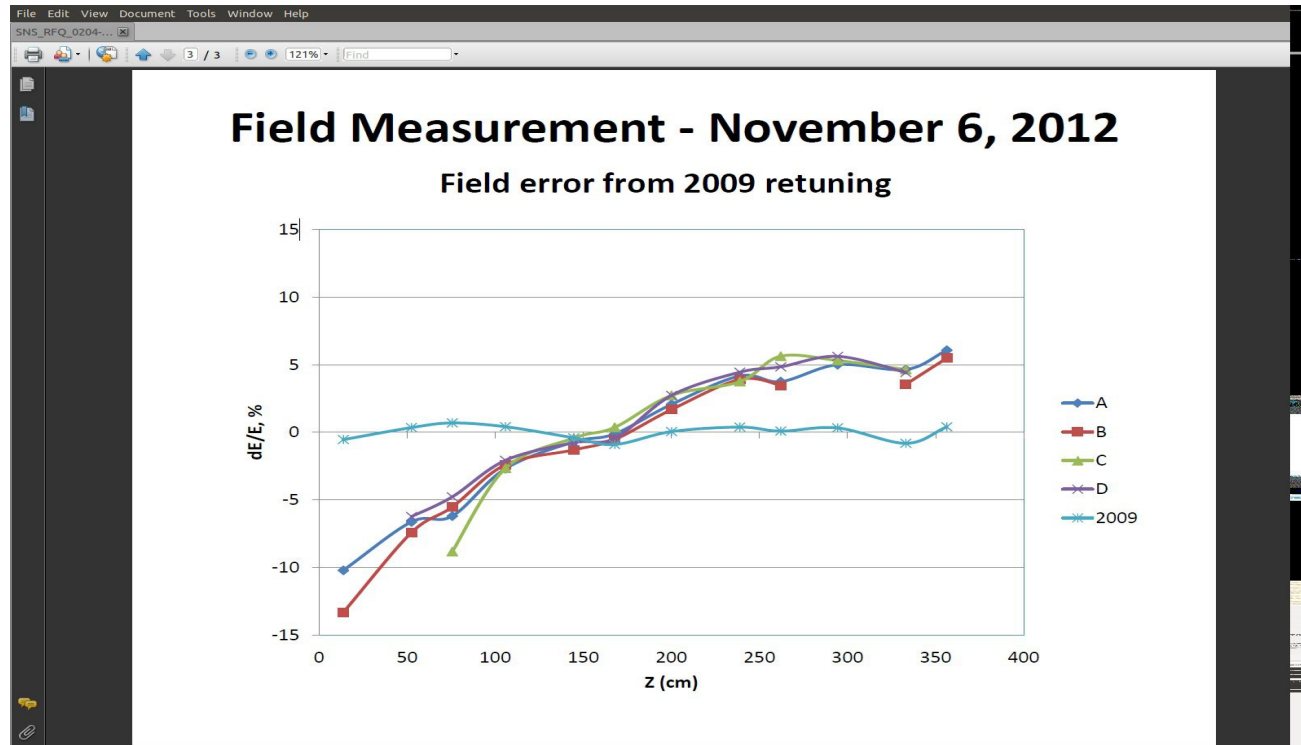


Where in the RFQ is there a frequency error?
Note that all 4 quadrants have a similar error.

Note that all data is from sensing probes. No bead pull data.

Aside: RFQ has been running at 7% duty factor for over 10 years, which translates to almost 1 year CW, or 3 years at 8 hours/day operation. There is possibly some vane tip erosion at the front end due to the ion source 12 cm away producing a high hydrogen pressure causing microdischarges.

Example, SNS RFQ Field Adjustment



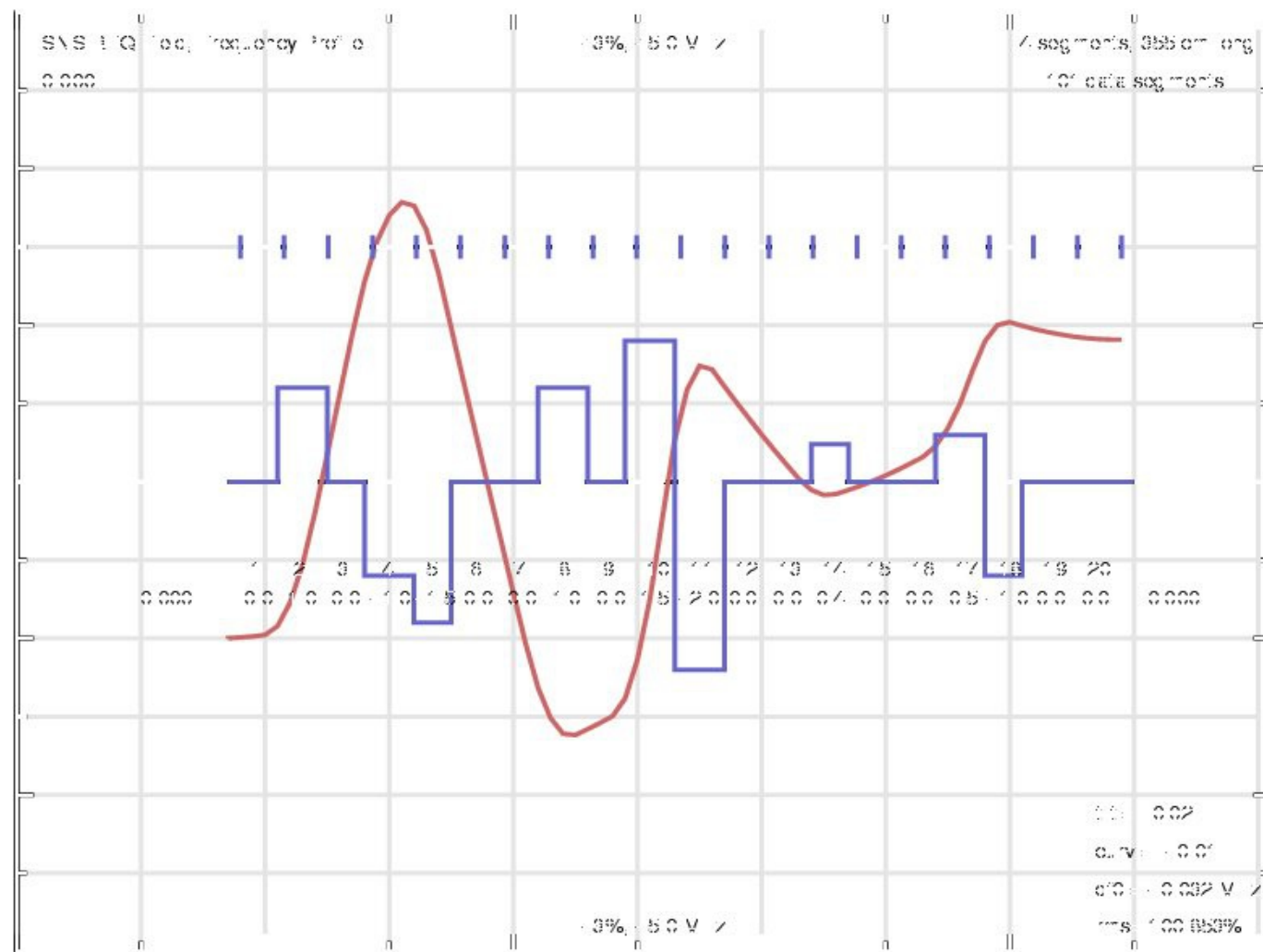
Where in the RFQ is there a frequency error?
Note that all 4 quadrants have a similar error.

Answer: compare with field basis set. Error is on the left-hand end.

The solution is to remove only **0.38 cm** from the first set of tuners as calculated with the RFQTUNE program.

A more Typical Tuning Problem

Red is the local field variation, blue is the calculated tuner positions to flatten the field.



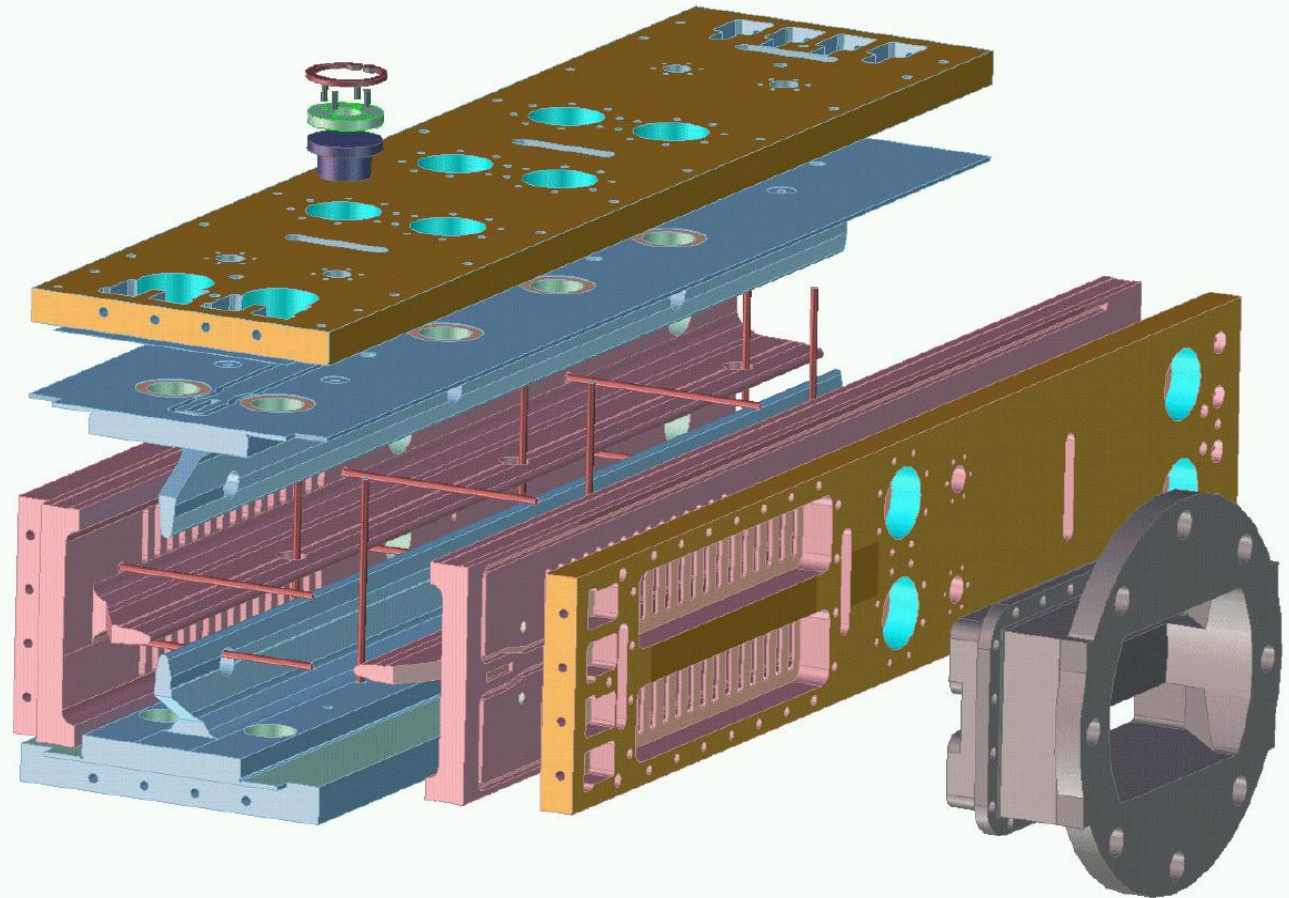
RFQ Mechanical Design

444 cm long

4 modules

80 tuners

2 drive ports



Easiest to pull bead through two top quadrants only. Need very high string tension to pull bead through bottom quadrants.

Bead will ride on vane tips: very inhomogeneous field, need to constrain bead to same location relative to beam axis.

Bead Properties

The frequency perturbation for a single round bead of relative dielectric constant ϵ_r and volume V_{bead} is

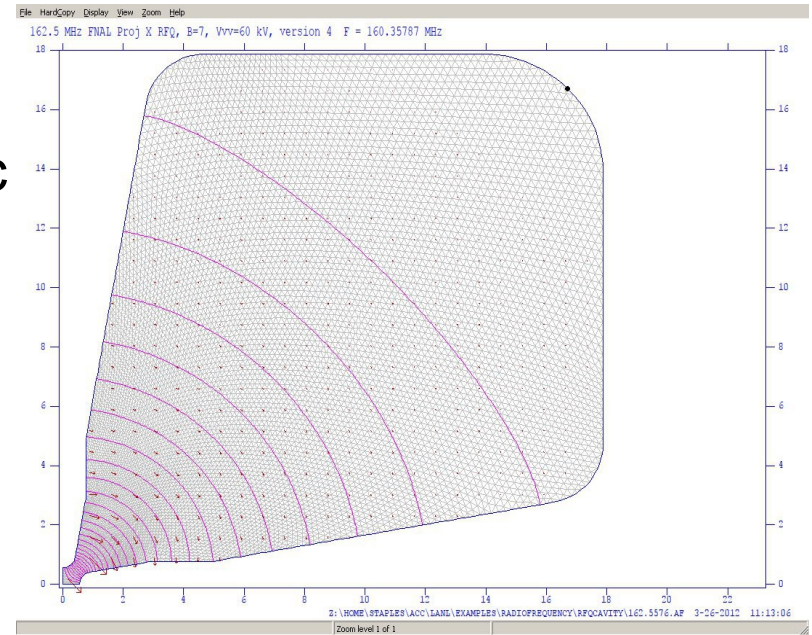
$$\frac{\Delta f_0}{f_0} = \frac{3 V_{\text{bead}}}{4 U_{\text{cavity}}} \frac{\epsilon_r - 1}{\epsilon_r + 2} \epsilon_0 E^2$$

The field in the region 1.5 cm from the beam axis where a bead will lie between two vanetips is about 4 MV/m. The stored energy in the full cavity is 1.0 Joule.

A metal bead 1 cm in diameter will perturb the field about 9 kHz.

Sapphire has a relative dielectric constant of 11.5, and will perturb the field by 7 kHz.

A frequency perturbation of at least 1 kHz is adequate.

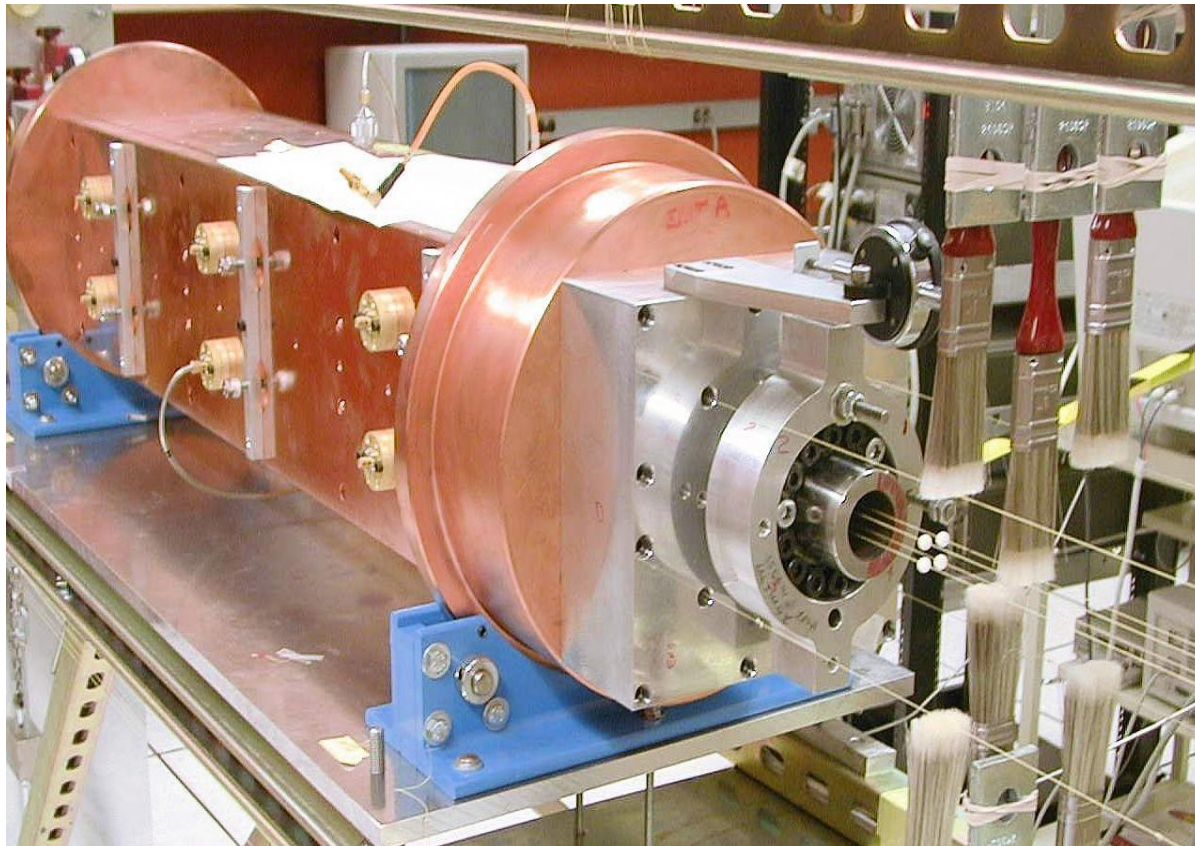


Bead Pull Apparatus Requirements

Beadpull apparatus used on the SNS 1 meter cold model

8 strings: 4 for electric field E, 4 for magnetic field H

Note paint brush vibration dampers



H-field measurements not useful – too noisy.

Four-quadrant E-field measurements critical in understanding pi-mode stabilizers. Field in all 4 quadrants same within measurement noise.

Bead Pulling Equipment

Fermilab will provide.

Equipment will attach directly onto RFQ modules?

444 cm overall length+ends

Also, pull bead through 1 or more modules

Automated bead pull, automated frequency recording

Resolution 1-2 cm is adequate

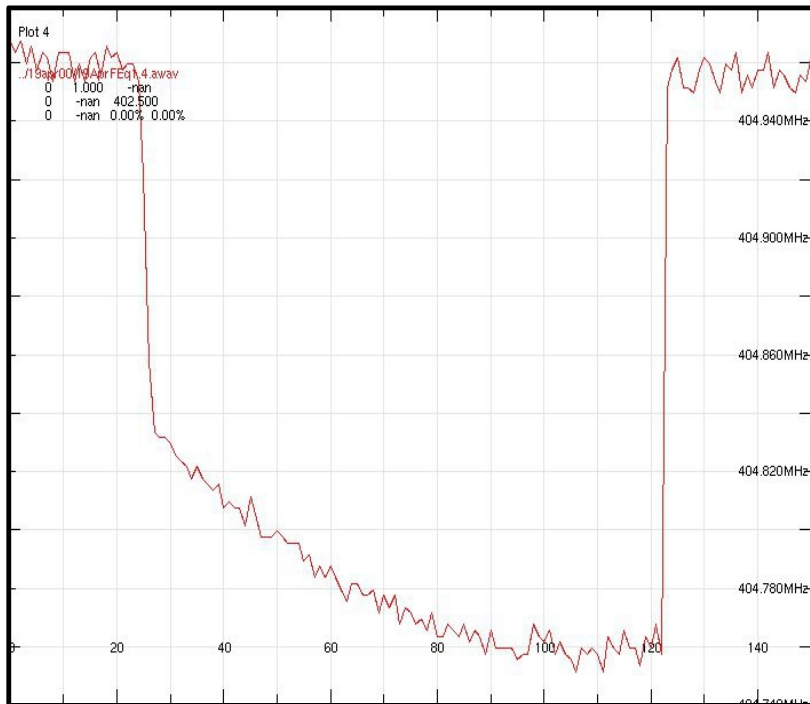
80 adjustable tuners in 20 groups, adjustable end pieces.

Easy access to tuners, and easy access to sensing loops for calibration.

FNAL has a complete bead pulling and data acquisition system.

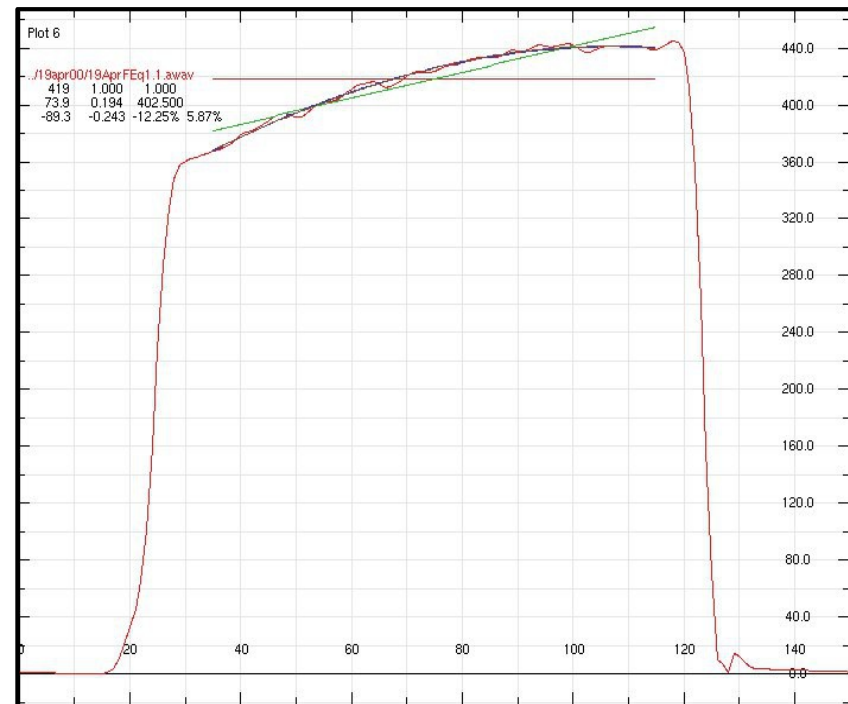
Massaging the Data before Analysis

The data will be noisy, have thermal drifts, and will need to be pre-processed.



Raw Frequency Data

Poor field flatness

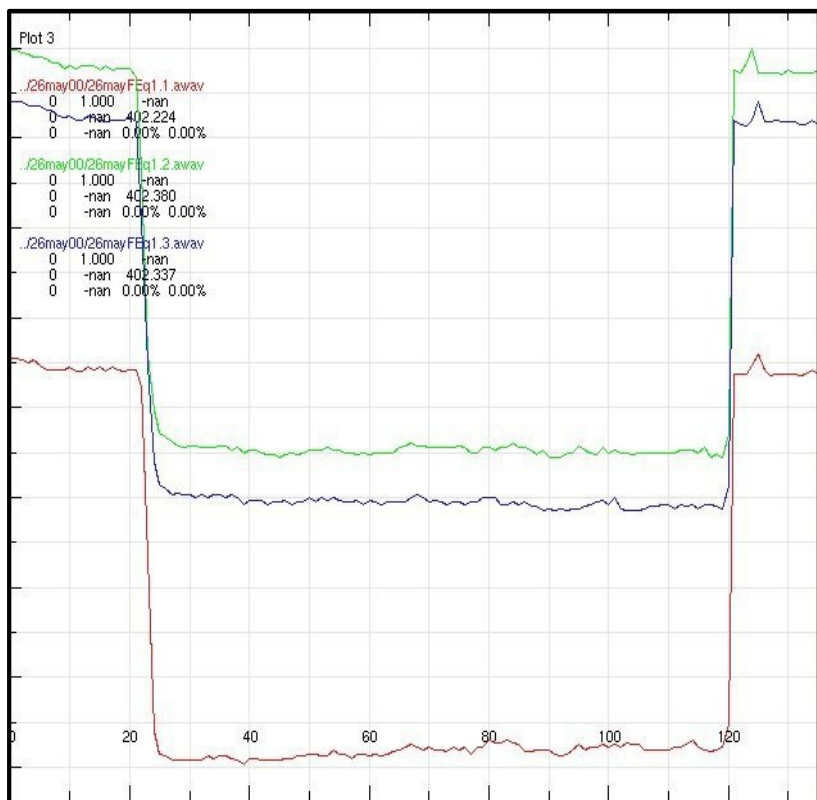


Drift removed, smoothed, square rooted.

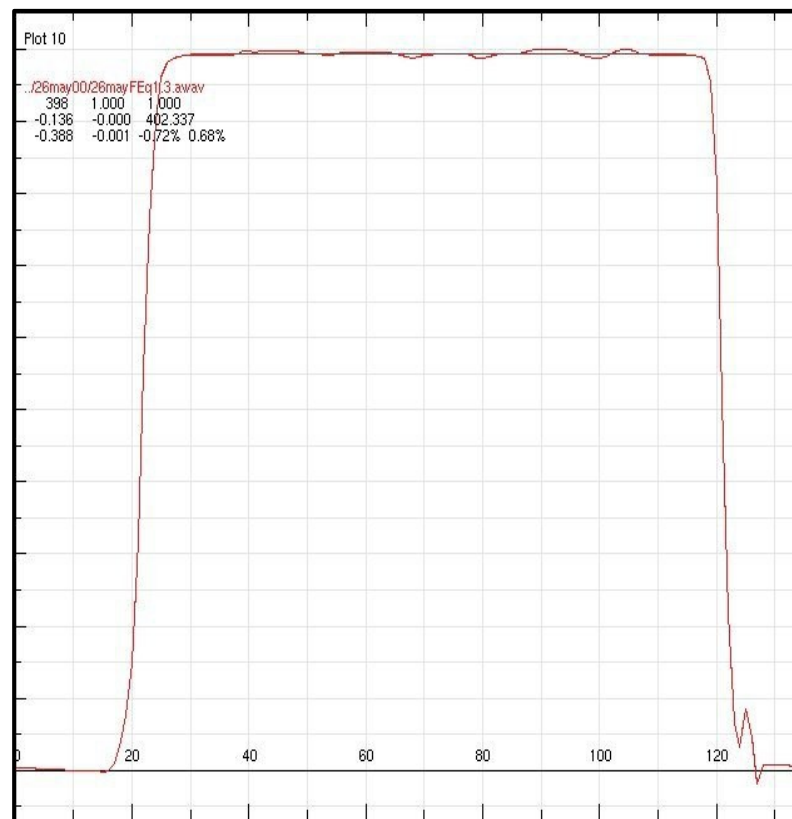
Some initial statistics: [tilt](#), [curvature](#)

Input data to rfqtune program

After Tuning



Raw data, 3 scans,
baseline frequency shifts



Smoothed data to RFQTUNE program

Preprocessor Program WAVES

```

register commands
avg      n i j      - replace in n average of i to j in i to j
c        m <= n      - copy m from n
cut      m n i j      - put points i thru j from n into m
dff2     m n i j      - put in m df(z) MHz in n from i thru j. needs f0, dz, rfqlth, 0 < E0 < 1
dff1     m n i j      - put in m first derivative of n from i thru j.
freq     n freq      - nominal frequency for this data set
flat     n i         - flatten n using i points from each end
g)et     n filename   - get file filename, put into n
lin      n Q         - linearize n around zero phase at with high cavity Q for large dfreq
list     n i j        - list contents of n from i to j
lsq      n i j        - calc lsq fit from i to j for n
max      n a          - scale max of n to a<1>
min      n a          - scale min of n to a<-1>
p)lot    n1 n2 ...    - plot registers ni
p)lotlsq n1 n2 ...    - plot registers with fitted lsq
put      n i j        - put value of j into i in data set n
scale    n m b        - scale n by m, offset b
set      n i j a      - set i to j of n to value a
shift    n delta      - shift n by delta
smax     n a          - set max of n to a<0>
smin     n a          - set min of n to a<0>
smooth   n sig        - gaussian smooth n with sigma <1.0>
sqr      n            - square n
sqrt     n            - take sqrt of abs of n
sum       m <= n1 n2 n3... - average of sum n1, n2 ..., put into m
tilt     n a          - tilt right hand side by a units
zero     n i          - reset zero reg n at data point i

Programming commands
proc name
  procedure body with $m $n indicating substituted parameters
end
call name variable list

General commands
*      comment      - enter a comment
f0     f0           - enter RFQ frequency [MHz]
dz     dz           - step size in cm between each data point
rfqlth L           - total RFQ length in cm
help                   - print this page
read   filename      - read an external data/control file
write  n cut1 cut2    - write a file of register n, with rfq lth at cut1, cut2
show                   - summarize input data
offline on/off/close  - control off-line output
init                   - clear all registers
quit                   - exit program
  
```

```

* 25 May 2000
* RFQ after braze operation

dz 1
rfqlth 93
f0 402.5

proc doit
get  $1 $4
put  $1 0 1
freq $1 $3
c    $2 $1
flat $1 20
avg  $1 0 18
avg  $1 127 150
zero $1 10
flat $1 20
smooth $1 1
sqrt  $1
zero  $1 10
flat  $1 10
zero  $1 10
lsq   $1 30 115
end

proc do2
c    $1 $2
zero $1 20
scale $1 -1
end

call doit 1 11 402.224 ../26may00/26mayFEq1.1.awav
call doit 2 12 402.380 ../26may00/26mayFEq1.2.awav
call doit 3 13 402.337 ../26may00/26mayFEq1.3.awav

call do2 21 11
call do2 22 12
call do2 23 13

pl 3
  
```

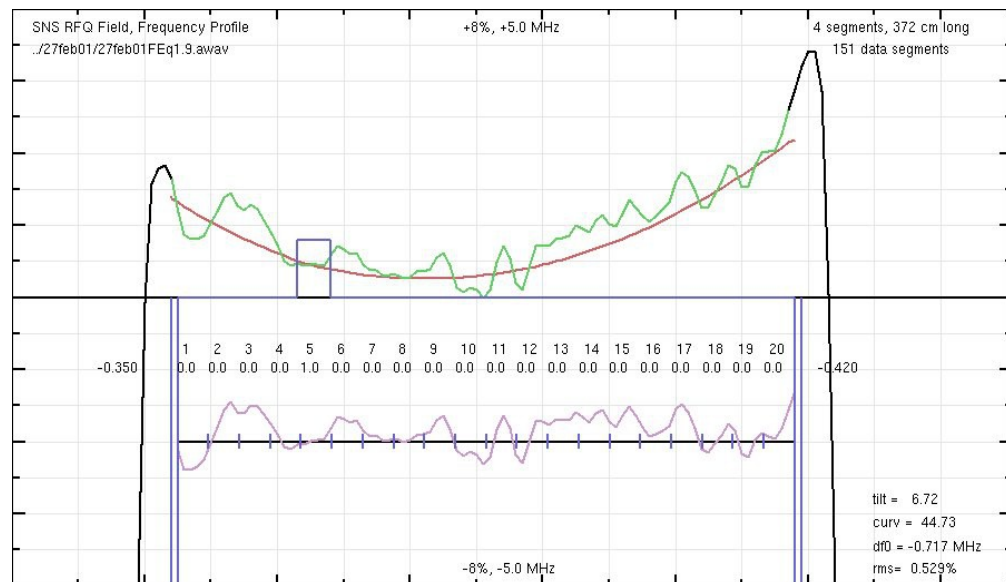
Incorporates a set of **very powerful vector operations** specifically written for bead pull data.

Can be formed into subroutines directed by scripts.

Typical instruction script with two defined procedures:

doit and **doit2**

Tuning program RFQTUNE



```
entrance tuner -0.350
tuner 1 0
tuner 2 0
tuner 3 0
tuner 4 0
tuner 5 1.000 MHz, 2.22 mm, 2.1 turns
tuner 6 0
tuner 7 0
tuner 8 0
tuner 9 0
tuner 10 0
tuner 11 0
tuner 12 0
tuner 13 0
tuner 14 0
tuner 15 0
tuner 16 0
tuner 17 0
tuner 18 0
tuner 19 0
tuner 20 0
exit tuner -0.420
```

```
e0 0.0280, delta E(z) initial condition
f0 402.686 MHz
sc 0.080 field graph scale (fraction)
scf 5.000 frequency graph scale (MHz)
nsegs 4
cut 25 117, 93 data points in calculation
sens 4.50 MHz/cm tuner sensitivity
offset -0.50 field error vertical offset on graph, -1 < offset < 1
```

Takes preprocessed data, and suggests tuner settings to flatten field.

Here the ends are tweaked, and tuner 5 is adjusted to give a correction (red).

While actually doing the tuning, the information should be presented in the easiest way to interpret. Here, the lead screw on tuner number 5 is required to be turned 2.1 turns. The entrance and exit end tuners are also adjusted to remove the field curvature.

The field scale is +/-8%, and the resulting field is within +/-1% (purple).

Data Format from the Bead Pull Apparatus

Contains the filename, followed by a list of frequencies recorded as the bead traverses the structure.

This file is read by the WAVES program
and the processed data set moved on to
the RFQTUNE program.

'23jun00FEq1.2'
402479597.52
402484597.52
402479597.52
402479597.52
402479597.52
402484597.52
402484597.52
402484597.52
402479597.52
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What's Needed

Bead pull physical setup

step motors motor drivers, kevlar string, (sapphire) beads, string puller

programmable network analyzer, probes, couplers

80 adjustable tuners

all 48 sensing loops in place, cabling, RF detector for loop calibration

Software

bead pull motor driving software

network analyzer data acquisition software

RFQ tune software, preprocessing software

database and data cataloging software

Procedure

LBNL will prepare two endpieces to allow bead pulls, if needed, of individual modules

At least one module will be dry assembled with endwalls to determine the body resonance before brazing.

All four brazed modules will be assembled with temporary adjustable tuners, temporary adjustable endwalls, drive loop and sensing loop for an S_{21} measurement to determine the overall resonance.

It may be desirable to configure the drive loop for critical ($\beta=1$) coupling. Only one loop is needed, and it would be a low-power device. We could also test the FNAL couplers, if ready.

Using the bead pull instrument, the field profile and base frequency of the RFQ will be adjusted to the required values.

All 48 sensing loops will then be calibrated. If a critically coupled drive loop is used, then the absolute S_{21} value of each sensing loop could be obtained.

Expected Results

A set of body tuner and end tuner positions that would then be translated into final fixed hardware.

The field profile of the RFQ would meet the requirement within the specified tolerance.

The measured Q of the RFQ would be obtained to determine the RF power requirement for full excitation with zero beam loading.

Recap

The end terminations significantly influence the overall resonance. The ends must be tuned to the body frequency by observing the field curvature during a bead pull.

The pi-mode stabilizers lock the fields in all four quadrants together. This reduces machining and assembly errors and protects the field symmetry against future changes in geometry (as with SNS).

The 80 tuners are grouped into 20 sets of four so the tuning problem has 20 variables plus the end resonances.

The vector basis set of the 20 tuners is not orthogonal. All field errors are the linear sum of this basis set and the two end resonances. All must also be adjusted to flatten the field at 162.5 MHz under typical operating conditions (CW after warmup).

Field errors due to local resonance errors scale as the square of the RFQ length. Tuning individual modules is probably not useful, except to ascertain rough frequency.